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14. ABSTRACT
The objective of our research program was to observe the temporal and spatial evolution of typhoon cold wakes, in particular we directly observed the mixing associated with turbulence generated by the strong air-sea interaction in a typhoon. These observations will be used to make quantifiable assessments of mixed layer models under the extreme conditions of a typhoon. We also observed the restratification of the cold wake from air-sea fluxes to understand the subsequent evolution of the cold wake after the typhoon had passed.

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typhoon, typhoon cold wake, air-sea interaction

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Observing the Evolution of Typhoon Wakes

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LONG-TERM GOALS

The long-term goal of this work was to observe, understand, quantify and parameterize upper-ocean mixing in the cold wake of a typhoon.

OBJECTIVES

The objective of our research program was to observe the temporal and spatial evolution of typhoon cold wakes, in particular we directly observed the mixing associated with turbulence generated by the strong air-sea interaction in a typhoon. These observations will be used to make quantifiable assessments of mixed layer models under the extreme conditions of a typhoon. We also observed the restratification of the cold wake from air-sea fluxes to understand the subsequent evolution of the cold wake after the typhoon had passed.

APPROACH

We made these observations during a ship-based survey of the typhoon cold wake that was undertaken to observe the restratification and collapse of the wake after the passage of a typhoon in the Western Pacific Ocean. The cold wake survey utilized a towed profiling temperature and salinity sensor and a tethered microstructure turbulence package. Also, we utilized newly developed Seagliders with microstructure sensors to examine the mixing structure of the coldwake.

TASKS COMPLETED

After several years of planning the observational field program, it was the focus of the work completed during this project. The planning phase involved several meetings of the Impact of Typhoons On the Pacific (ITOP) and Tropical Cyclones Study 2010 (TCS2010) investigators. The integration and testing of microstructure sensors on the gliders was also completed. During the final year we completed the observational phase of the program. Daily teleconferences between ITOP and TCS2010 investigators lead to the decision to conduct the cold wake survey cruise in Typhoon Fanapi. All of the observational assets were marshaled, and a successful cruise on the R/V Revelle was undertaken to sample the cold wake. The cruise itself was logistically difficult, as it required organizing investigators and coordinating travel for participants from 5 U.S institutions and 2 Taiwanese institutions. But all the planned participants were able to arrive on time for the ship to get underway from Kaoh-siung, Taiwan on 21 September 2010 just 1 day after Typhoon Fanapi passed over Taiwan. The cruise ended on 11 October 2010 in Okinawa, Japan.

During the cruise, we studied the cold wake formed by Typhoon Fanapi, a category 3 typhoon that formed on 14 September 2010, made landfall in Taiwan on 19 September, and dissipated on 22 September over mainland China. During the initial week of the survey on the R/V Revelle, a well-defined cold wake was identified and sampled in the area east of the Ryukyu Islands (Figure 1). The wake was 3 days old when it was initially sampled, and was crossed on 3 occasions over 4 successive days in the 21-25 September 2010 (Figures 2 and 3). Turbulence levels were measured with a VMP-500 free-falling turbulence profiler, equipped with dual shear and temperature microstructure probes as well as a Seabird CTD. The system was used to profile to depths of 200 to 400 m, well into the mixed-layer / thermocline transition layer. These are the first microstructure observations ever made in the cold wake of a tropical cyclone.

As a summary of the cruise accomplishments:

- 2917 underway-CTD profiles recorded
- 172 vertical microstructure profiles
- 21 CTD profiles with water samples (12 bottles per cast for biogeochemical study)
- 10 gliders deployed
- 3 sediment trap deployed
- 3 superdrifters recovered, 1 ADOS drifter recovered
- Coordinated operations with the C-130 (for AXBT calibration and for observation of an air deployment of a float)

RESULTS

We observed that Typhoon Fanapi created a significant cold wake (~2°C). Our survery also found that solar radiation quickly capped the cold wake, making it difficult to detect in satellite sea surface temperature images, but in-situ observation revealed that the cold wake persisted for several weeks. Phenomena on several time and spatial scales were observed to have a role in the evolution of the cold wake, e.g. near inertial waves, mesosale eddies, and propagating tidal internal waves.

IMPACT FOR SCIENCE

These novel observations made during the cold wake survey cruise are now being analyzed, and a series of coordinated journal articles are being prepared. We are in the process of synthesizing the ship observations, glider measurements, float and drifter measurements and remote sensing to adequately describe the evolution of the wake. A summary of the ITOP program, featuring the cold wake cruise after Typhoon Fanapi has been published (D'Asaro et al. 2011), and an initial manuscript on the cold wake observations has been submitted (Mrvaljevic et al. 2012).

RELATED PROJECTS

Related to this project is my work in understanding and parameterizing mixing in global ocean models, such as the Community Earth System Model (http://www.cesm.ucar.edu/), and an NSF funded Climate Process Team on the same subject (http://www-pord.ucsd.edu/~jen/cpt/).

FIGURES/PICTURES

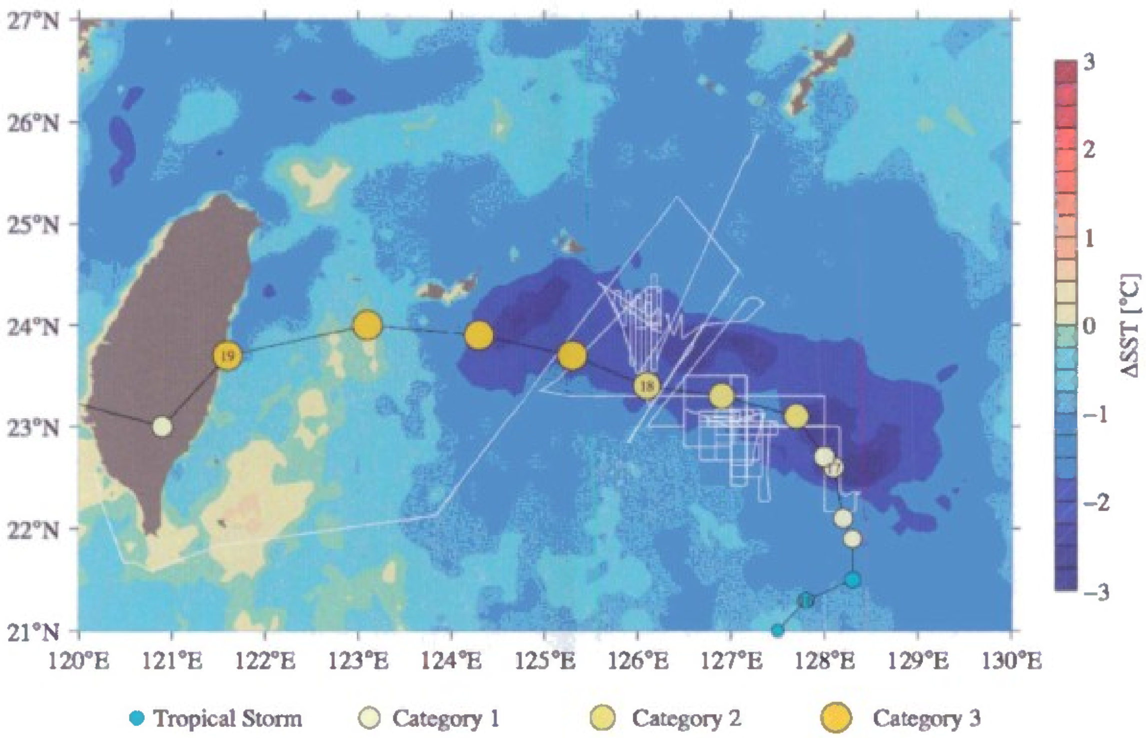

Figure 1 shows the cruise track of the cold wake cruise overlaid on top of the sea surface temperature difference between pre-Fanapi period (September 13-15, 2010) and the post-Fanapi period (September 19-21, 2010).

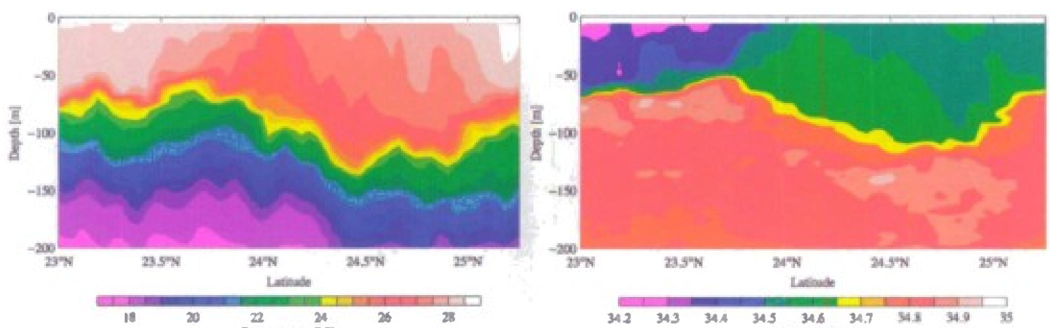

Figure 2: shows the vertical cross-section of the first crossing of the cold wake with temperature in the left hand panel, and salinity on the right. They show the mixing of the water from below the mixed layer upwards by the strong mixing during the typhoon

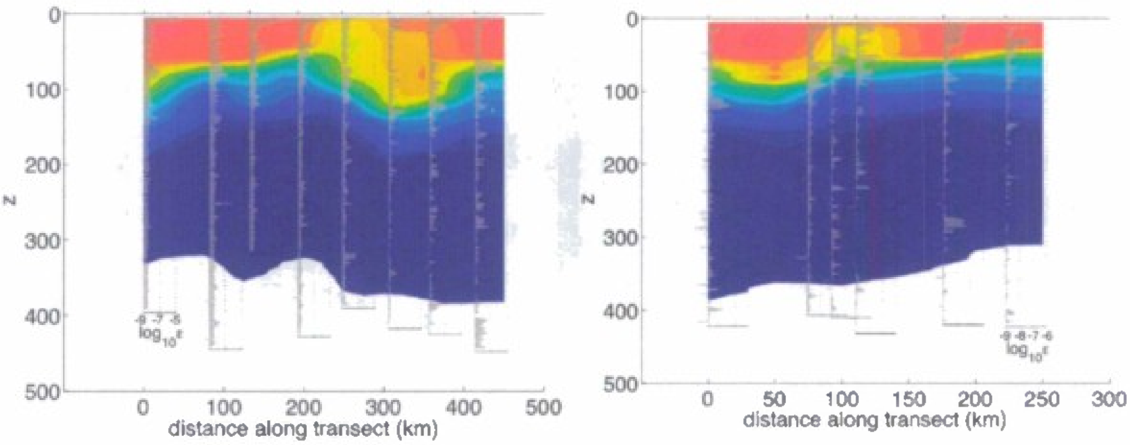

Figure 3: Temperature and turbulent dissipation rate (ε) across the region of the cold wake for section 1 (left hand panel) at t=3 days after the passage of the typhoon, and the cold wake for section 2, at t=3.5 days after the passage of the typhoon. Distance along the transect runs from south to north. Temperature contours are from 15 to 30 C, and the cold wake signal in clearly visible between the 200 to 400 km section of the transect.

REFERENCES

D'Asaro, E., P. Black, L. Centurioni, P. Harr, S. R. Jayne, I.-I. Lin, C. Lee, J. Morzel, R. Mrvaljevic, P. P. Niiler, L. Rainville, T. Sanford, and T. Y. Tang, 2011: Typhoons and the ocean in the western North Pacific: Part 1. *Oceanography*, **24**, 24–31.

Mrvaljevic, R. K., P. G. Black, L. R. Centurioni, Y.-T. Chang, E. A. D'Asaro, S. R. Jayne, C. M. Lee, R.-C. Lien, J. Morzel, P. P. Niiler, L. Rainville, and T. B. Sanford, 2012: Evolution of the cold wake of Typhoon Fanapi. *Geophysical Research Letters*, submitted.